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Feasibility of a Retro-Rocket Dissemination Concept as Applied to an Artillery Shell

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FEASIBILITY OF A RETRO-ROCKET DISSEMINATION CONCEPT AS APPLIED TO AN ARTILLERY SHELL

by

Raymond P. Tytus
Craig R. Allan

Chemical Laboratory

October 1976

DEPARTMENT OF THE ARMY
Headquarters, Edgewood Arsenal
Aberdeen Proving Ground, Maryland 21010

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The feasibility of incorporating a "retro-rocket" agent dissemination technique into an artillery shell modeled on the 155-mm XM687 was determined. For two hypothetical rocket motor designs, calculations were made of shell displacement and velocity for representative propellant burn times and initial shell velocities. This use concept of the "retro-rocket" was found unfeasible. The limited volume, high inert weight and wide range of delivery velocities of artillery shells prevents the use of sufficiently powerful rocket motors to meet all shell delivery conditions and provide adequate payload capacity.

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FEASIBILITY OF A RETRO-ROCKET DISSEMINATION CONCEPT AS APPLIED TO AN ARTILLERY SHELL

I INTRODUCTION.

This report investigates the feasibility of adapting a "retro-rocket" dissemination concept to a liquid-chemical-fill artillery shell. In such an application a rocket motor located in the nose of the munition would be ignited at a predetermined height above the target. The resulting high pressure gases would pressurize the agent compartment thus forcing agent through a discharge tube into the rocket exhaust plume. Simultaneously, the gases would produce a reverse thrust which would retard the shell to extend the period of time available for agent discharge while the shell is within an effective standoff distance from the target. As a result, the agent conceivably would be rapidly disseminated over a large target area.

Initial studies of this concept were performed by Stanford Research Institute.[1] Their experimental work with a statically fired unit indicated the potential effectiveness of this approach for producing rapid target coverage with fine aerosols made from nonvolatile liquids. This approach was studied further at Edgewood Arsenal through experimental studies designed to establish cloud plume coverage and by a theoretical evaluation of the concept applied to a free fall bomb and a rocket.[2] When statically fired downward from a 50-foot tower, the disseminator produced an agent cloud which reached ground level in 0.4 second and spread to a diameter of 100 feet in less than 3 seconds. The disseminator contained 3.2 gallons of fog oil* and a 5-lb propellant grain which burned for 1.2 seconds. The theoretical study conducted concurrently indicated that a bomb falling at 200 feet per second could be stopped in flight in 100 feet with a grain comprising 3% of the total bomb weight. For representative grain and agent weights and for a 1-second burn, the rocket, if traveling at 500 feet per second, could be stopped in a distance of 200 feet, but, if traveling at 1,000 feet per second, would be retarded to a residual velocity of 285 feet per second. The deceleration would take place in a distance of 650 feet. It was concluded that "retro-rocket" dissemination was a feasible concept and merited further evaluation.

The application of interest, of the "retro-rocket" concept in this report is to an artillery shell, which, if modified into a "retro-rocket" rather than an explosive disseminator, conceptually might be more efficient because of increased target area coverage in shorter times with greater amounts of effective agent at ground level. Considered in this study are the effects of basic "retro-rocket" design parameters on the displacement and payload of shells having the dimensions, weight and terminal velocity range of the 155-mm XM687. Figure 1 depicts the concept of such a shell which has been modified for "retro-rocket" dissemination on the basis of the same design that was successfully used in the experimental programs at Stanford Research Institute and Edgewood Arsenal.

II PROCEDURES AND RESULTS

Three factors are of particular concern to this study: the basic feasibility of incorporating a rocket motor into an XM687 artillery shell case, the realizable agent payload which would be available in the modified munition, and the effects produced on shell flight by the retrofiring forces. The approach taken was to determine first, as a goal, what thrusts would be required to meet the idealized use concept of stopping the shell in flight above a target. The ability of the "retro-rocket" shell to meet these requirements was then evaluated by calculating the thrusts

* A low viscosity petroleum oil.

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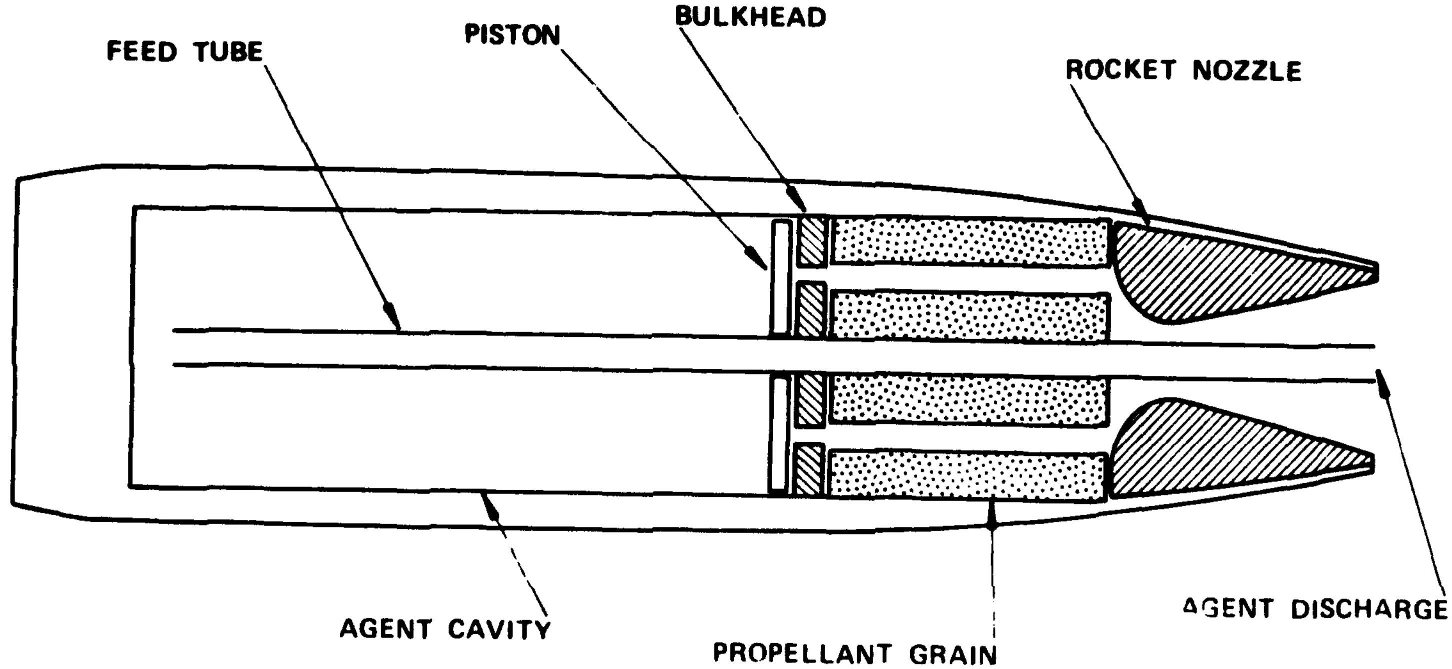

Figure 1. Schematic of Artillery Shell Adopted for Retro-Rocket Dissemination

which actually could be generated by a rocket motor designed to fit within the shell. Based on the nozzle and propellant lengths dictated by the motor design, residual shell volumes available for agent payload were determined. For the maximum and minimum thrust motors specified by this analysis, shell displacement and final velocity for a range in propellant burn times were then calculated.

A. Thrusts Required to Stop the Shell in Flight.

Calculations were made to determine the thrusts necessary to stop the shell under representative use conditions. An initial total shell weight of 93 lb and terminal velocities of 500, 750, 1,000 and 1,250 feet per second were considered. These values are representative of the weight of the XM687 and the velocities it can achieve. As the inert hardware of the XM687 weighs approximately 80 lb, a weight of 13 lb was assigned to the consumables, i.e., propellant plus payload, to establish a basis for the calculations. The weight loss due to grain consumption and payload discharge was included; however, gravity and air drag were neglected as minor effects for these calculations.

The equation for rocket velocity is[3]

$$\nu = \nu_o + \frac{T\tau_B}{K W_T} g \ln\left(1 - K\frac{\tau}{\tau_B}\right) \qquad (1)$$

where

ν_o = initial velocity

T = thrust

τ_B = propellant burn time

g = acceleration due to gravity

W_T = total shell weight

K = the ratio of the consumable weight to total shell weight

and

τ = time after ignition.

The stop condition at the end of burn, i.e., $\tau = \tau_B$, was found by setting the equation equal to zero and solving for thrust, i.e.,

$$T = \frac{-\nu_o K W_T}{\tau_B g \ln(1-K)} \qquad (2)$$

All values in the equation are known except for τ_B, which was varied from 0.1 to 1.0 second. The calculated values of thrust versus burn time as a function of initial velocity are plotted in figure 2. The data shows that very high thrusts are required if the shell is to be stopped rapidly from these initial velocities.

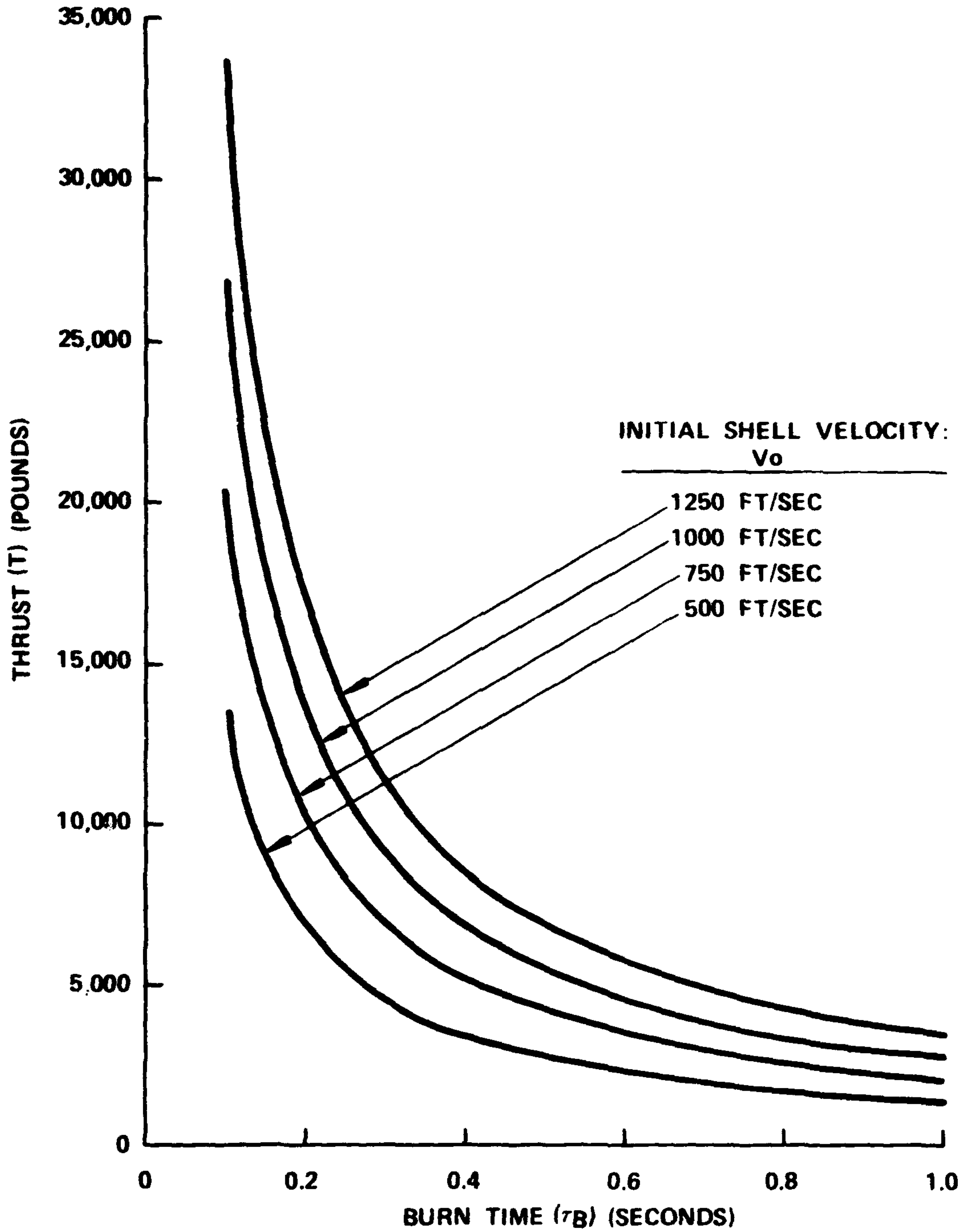

Figure 2. Thrust Required to Stop the Shell

B. Thrust Produced by Shell-Limited Nozzle Design.

In order to determine the actual rocket thrusts which can be produced, a standard De Laval rocket motor nozzle configuration was adapted to fit within the shell case[4] (figure 3). The effective diameter of the nozzle is limited to 4.75 inches by the usable inside diameter of the shell. Therefore the total length of a nozzle of this design and diameter is 7.5 inches. The thrust which could be produced by this nozzle was then calculated. The thrusts which would result if the length of the divergent exit cone was reduced were also calculated to evaluate the effect on thrust of shortened nozzles whose use would allow rocket motor volume within the shell to be reduced.

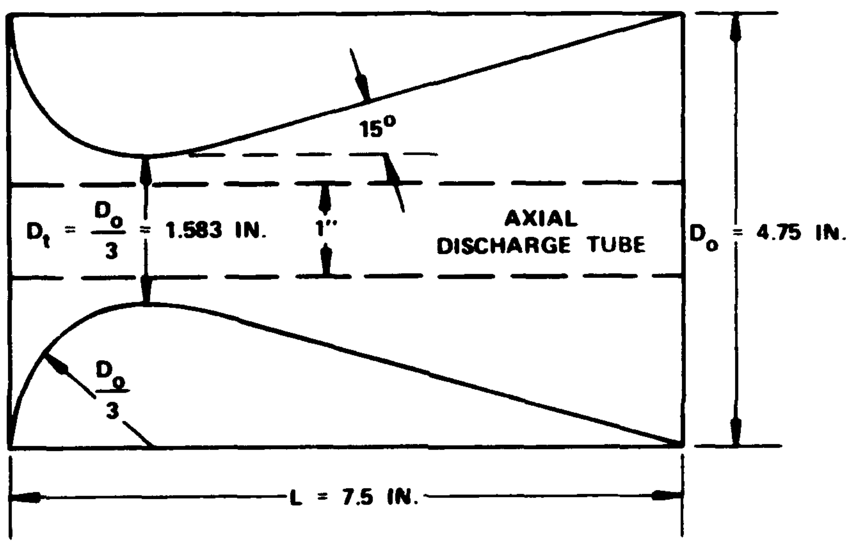

Figure 3. Nozzle Design

Thrust is a function of combustion chamber conditions and nozzle design and is expressed as:[5]

$$T = C_F P_c A_t \tag{3}$$

where

C_F = the optimum thrust coefficient

P_c = chamber pressure

A_t = nozzle throat area

Using the value of A_t, corrected for the axial, 1-inch-diameter discharge tube, assumed for this design, expansion ratios E are calculated, where $E = \frac{A_e}{A_t}$ and A_e is the nozzle exhaust area for each nozzle length. From standard rocket-engineering graphs of optimum nozzle expansion and using 1.27 as the ratio of specific heats of the exhaust gases, values of C_F and pressure ratios were obtained for each E.[6] As pressure ratio equals $\frac{\text{chamber pressure}(P_c)}{\text{outlet pressure}(P_a)}$ and P_a = 14.7 psi, values of P_c are determined. Thrust can then be calculated. The thrusts and corresponding chamber pressures required to support these thrusts are plotted in terms of nozzle length in figure 4. It is seen that available thrust is strongly dependent on nozzle length and that the maximum thrust available from this nozzle is 4,600 lb which corresponds to the full expansion condition, i.e., maximum possible nozzle exit area. For constant chamber pressure, the thrust is a constant which is independent of burn time. Therefore, when the 4,600-lb maximum available thrust is compared with the thrust requirements shown in figure 1 it is seen that a nozzle can be fitted into the shell which would permit the shell stop condition to be met over the full range in initial velocities if the required chamber pressures and sufficiently long burn times can be obtained from the propellant.

C. **Propellant Surface Area Requirements.**

The thrusts which can be generated by the nozzle are contingent upon the assumption that the prepellant grain can actually develop the required chamber pressures indicated in figure 4. To evaluate this condition, a propellant composition was selected and calculations were made to determine the actual pressures that could be obtained.

The single base propellant composition, ALT-161,[7] was selected for the design because it contained a flash suppressant, $KClO_4$, and exhibited high burn rates, two potentially desirable properties for this application.

For a rocket motor operating at a constant pressure, the law of conservation of matter[8] states that

$$\dot{W}_p = \dot{W}_g + \dot{W}_e \tag{4}$$

where

$\dot{W}_p$ = the weight rate of propellant consumption

$\dot{W}_g$ = the weight rate of increase of gases in the surrounding free chamber volume

and

$\dot{W}_e$ = the weight rate of flow of discharge gases through the exit nozzle.

This equation can be rewritten as[8]

$$S_c r_o \rho_p = S_c r_o \rho_g + C_w P_c A_t \tag{5}$$

where

S_c = the total burning surface area of the grain

r_o = the linear burning rate

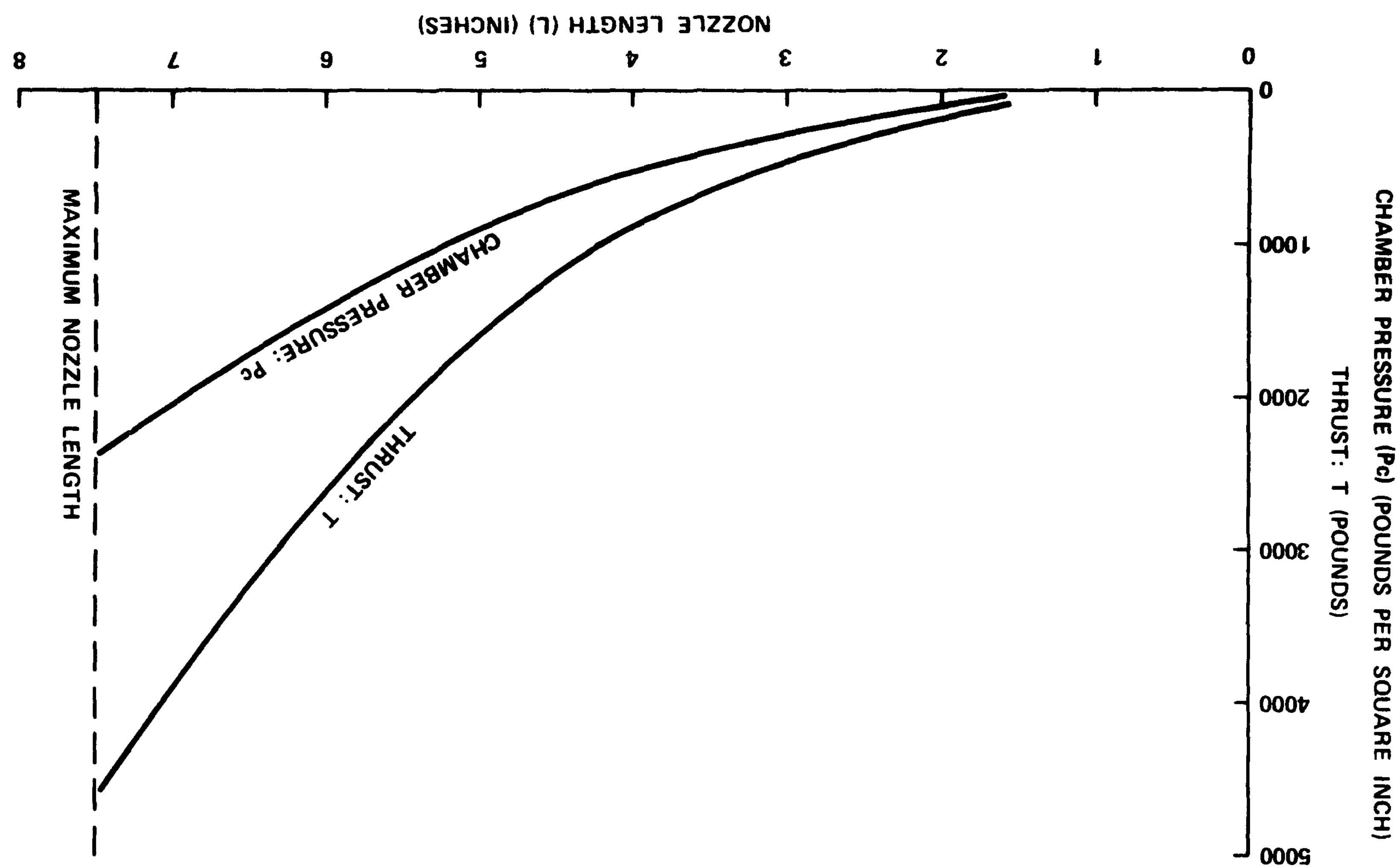

Figure 4. Nozzle Thrust and Chamber Pressure

ρ_p = the density of the propellant

ρ_g = the density of gases produced

C_w = the experimentally determined weight flow coefficient

P_c = is the chamber pressure

and

A_t = the throat area of the nozzle.

When rearranged in terms of S_c/A_t defined as K_n (propellant area ratio)

$$K_n = \frac{S_c}{A_t} = \frac{C_w P_c}{r_o(\rho_p - \rho_g)}.$$

Values of K_n, and therefore S_c, can be determined as a function of P_c, from the burning characteristic data of this propellant.[3] The calculated values of S_c for the range of required chamber pressures taken from figure 4 are plotted in terms of corresponding nozzle length in figure 5, a. Because the minimum combustion pressure at which the ALT-161 propellant will reliably burn is 700 psi,[9] S_c is restricted to values no less than 168 square inches. This restriction in turn establishes a lower boundary on nozzle length of 4-1/2 inches.

D. **Propellant Configuration Requirements.**

A propellant design must be established to determine if the above surface area requirements can be met with a grain which could be contained by the shell. An internal-external grain design was chosen to provide a high surface area per unit length, allow fast burn times, and provide reasonable strength to withstand shell setback forces. This grain is composed of two cylindrical, concentric sleeves. The larger sleeve with a 4.75-inch O.D. was designed to fit within the shell case. The smaller cylinder had an I.D. of 1 inch which allowed it to fit over the 1-inch axial discharge tube. The web thickness of each sleeve is equal and is varied to produce the burn times of interest. The maximum burn time is limited by the maximum web thickness which will still allow ignition of the adjacent inner sleeve surfaces. Because of the diverging direction of propellant consumption, the surface area remains constant while burning.[10]

For this configuration:

$$S_c = \pi(D_o + D_1)\,L_p \qquad (7)$$

where

D_o is 4.7 inches

D_1 is 1 inch

L_p is propellant length

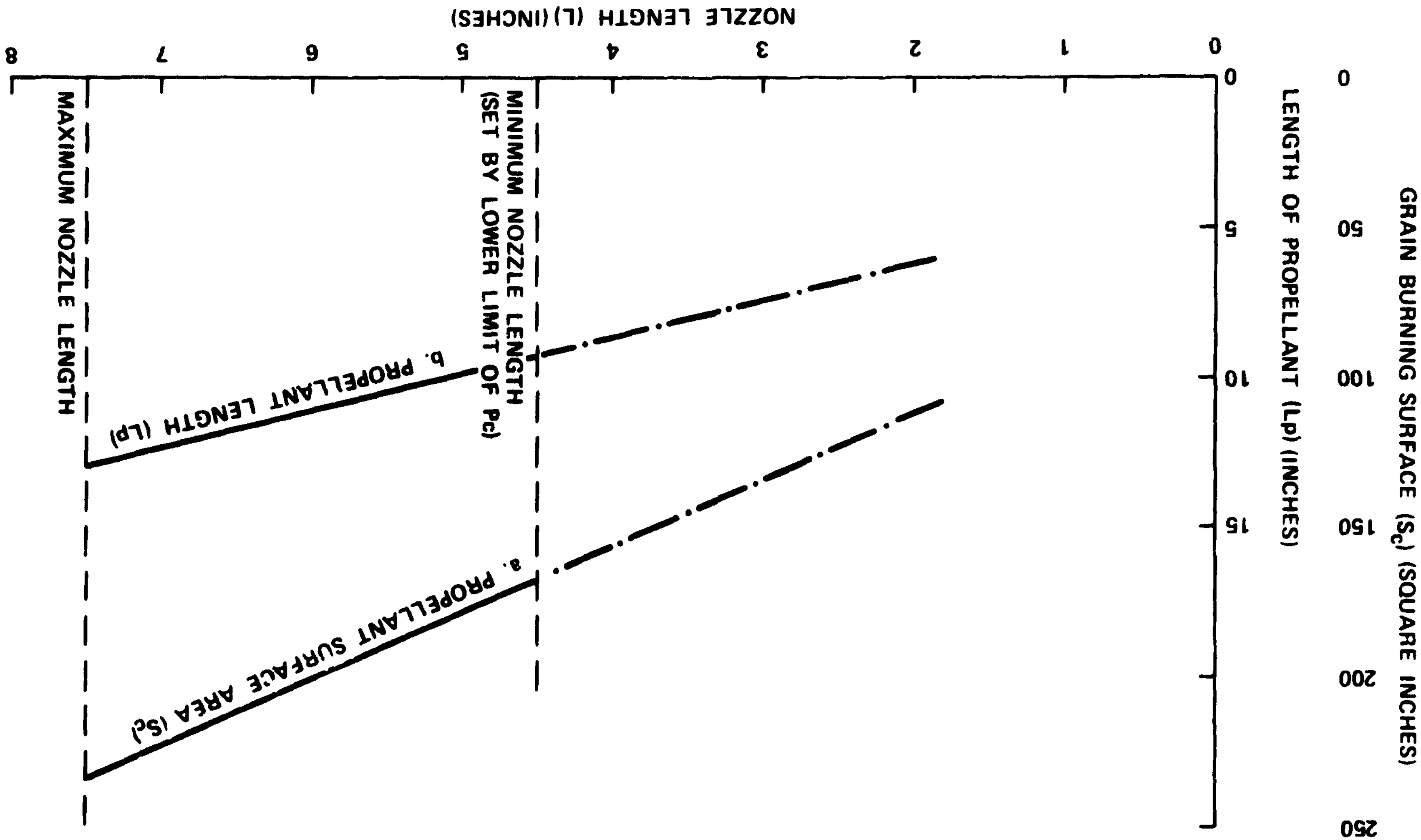

Figure 5. Propellant Design Requirements

Based on the range of values of S_c from figure 5.a. propellant lengths required for this grain configuration as a function of nozzle length were determined (figure 5.b). Propellant lengths range from 12.9 inches for the maximum thrust motor design to 9.3 inches for the minimum thrust design.

E. **Shell Length Requirements.**

Having established the possible range of nozzle lengths and corresponding grain lengths required for the rocket motor designs which could be adapted to this shell. the residual lengths available for agent payload when these motors are installed into the shell case can then be determined. The internal length of the main body section of the XM687 was estimated to be 21.5 inches. Agent compartment partitions totaling 1.8 inches in length. as well as 1 inch assigned to accommodate the pressure bulkhead and the piston required by the "retro-rocket" design. reduce the cavity length available for agent and rocket motor to 18.7 inches.

To incorporate the 4.75-inch exit diameter nozzle which produces the maximum 4.600-lb thrust condition requires that the nozzle be located in the forward end of the main body section. The ogive section can not be used for this design. As the length of this nozzle is 7.5 inches and the length of its corresponding propellant grain is 12.9 inches (figure 5) total rocket motor length is 20.4 inches. Since the required length of this rocket motor exceeds the available cavity length of the shell, no agent payload can be carri- n this case

To determine the maximum payload which could be obtained. the nozzle was moved forward into the ogive section and the propellant placed at the most forward end of the 21.5-inch long main cavity section. In this position the expanding throat of the nozzle is intercepted by the decreasing profile of the ogive to result in a nozzle length of only 5.2 inches. From figure 5 the corresponding propellant length is 10.2 inches. Reducing the total main cavity length by this propellant length and the 2.8 inches required for the partitions and hardware produces a length of 8.5 inches available for payload. If a 4.25-inch-inner-diameter agent container which is 90% filled is assumed. an agent payload of approximately 4 lb could be delivered by this "retro-rocket" shell design. As shown in figure 4. this gain in payload. which is obtained by shortening the nozzle. i.e.. reducing its exit area, is offset by a loss in available thrust The thrust is reduced from 4.600 to 1.750 lb.

F. **Shell Residual Velocity and Displacement.**

To evaluate the influence of the reverse rocket thrust on shell flight. residual velocities and displacements were calculated for the two previous rocket-motor designs. These two designs. which are used to represent the approximate performance limits of the XM687 shell modified for "retro-rocket" dissemination. represent the conditions of maximum attainable thrust. but negative payload (assumed to be zero for these calculations). and minimum thrust. but maximum payload. The calculations were made for shells traveling at 500 and 1.250 feet per second at the time of propellant ignition. the two velocity limits of the XM687. and for the range of possible burn times. The burn times wer- based on the burn rates of the chosen propellant which in turn are a function of the chamber pressure required by the given thrust level being considered.

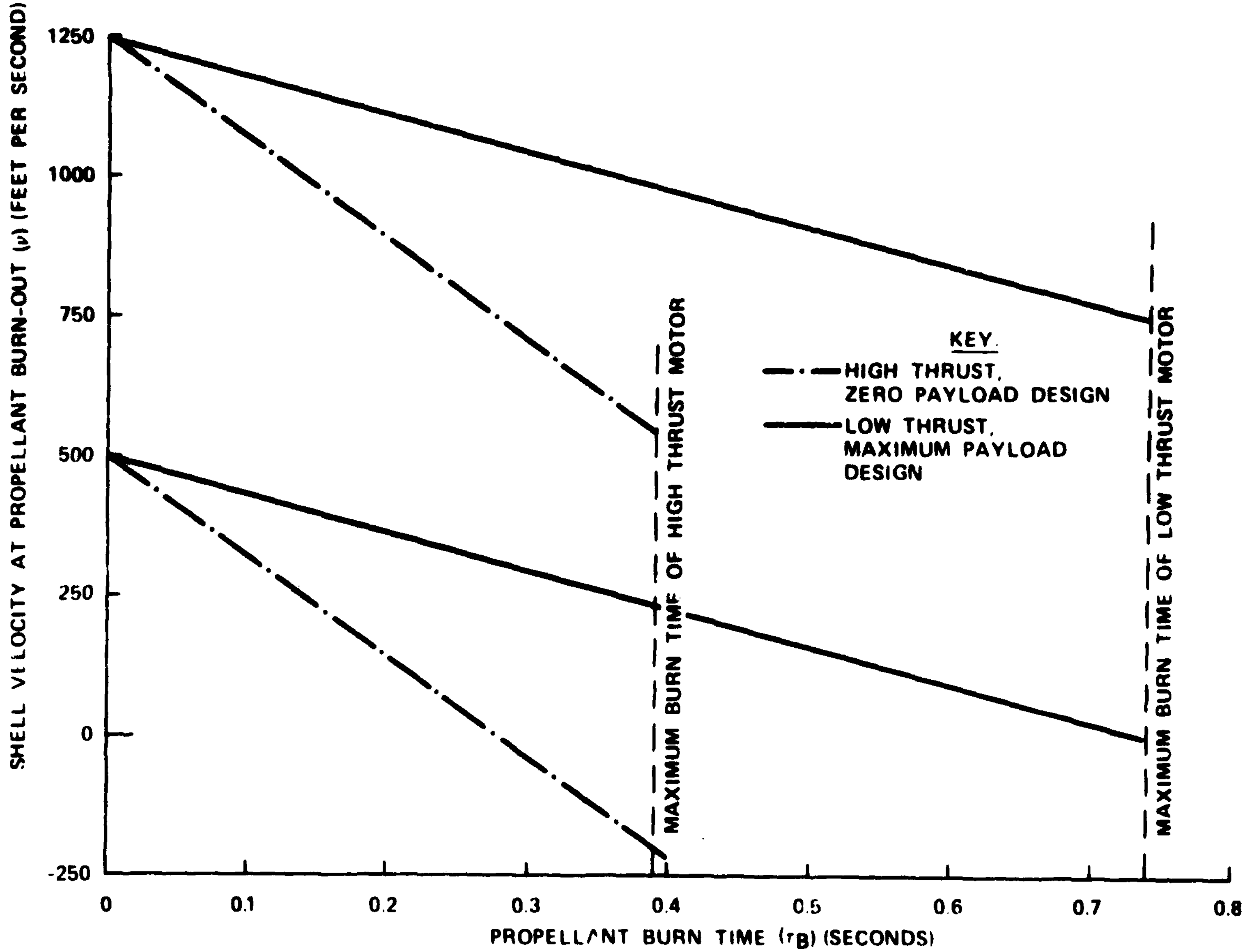

Figure 6. Shell Velocity at End of Propellant Burn

Residual shell velocity at propellant burnout (ν), and displacement (S) were determined by solving the rocket velocity and displacement* equations at $\tau=\tau_B$

$$\nu = \nu_o + \frac{T\tau_B g}{KW_T} \ln\left(1-K\frac{\tau}{\tau_B}\right) \tag{8}$$

$$S = \nu_o\tau - \frac{T\tau_B^2 g}{K^2W_T}\left[\ln\left(1-K\frac{\tau}{\tau_B}\right) + K\frac{\tau}{\tau_B}\left[1-\ln\left(1-K\frac{\tau}{\tau_B}\right)\right]\right] \tag{9}$$

All parameters are known or can be calculated from the preceding data. Maximum burn times are established by assuming that a 1/2-inch minimum web separation was required for ignition of the propellant surfaces. For the maximum thrust condition, i.e., 4,600 lb, the maximum burn time is 0.39 second and for the minimum-thrust condition, i.e., 1,750 lb, the maximum burn time is 0.74 second.

The calculated residual velocities are shown in figure 6. Both rocket motors are capable of stopping the shells in flight from an initial velocity of 500 feet per second. While the low-thrust motor requires its maximum burn time, i.e., maximum propellant weight, to stop the shell, the high-thrust motor requires only a 0.28-second burn time. Use of longer burn times, up to the maximum of 0.39 second, would result in this shell reversing direction. Interpolation of the data indicated that the maximum initial shell velocity from which the high-thrust motor can stop forward motion is 700 feet a second. For the maximum initial shell velocity of 1,250 feet per second, neither motor was able to stop the shell and even the high-thrust motor containing its maximum propellant weight could retard the shell to a velocity of only 550 feet per second at burnout.

The corresponding shell displacements at the end of propellant burn are shown in figure 7. Increased burn times which produce lower final shell velocities produce greater shell displacements. For the 500-foot-per-second initial shell-velocity condition, the high-thrust design produces a shell displacement of 75 feet at a 0.28-second burn time; the point at which the rocket motor has stopped forward shell motion. For the low-thrust design at this initial shell velocity, a displacement of 190 feet is required to stop the shell. Considerably greater shell travel occurs during propellant burn at initial shell velocities of 1,250 feet per second. Displacements of up to 345 and 730 feet are found for the high- and low-thrust motor designs respectively.

III. DISCUSSION

Based on the component designs and operating conditions used for this analysis, application of the "retro-rocket" dissemination concept to the XM687 artillery shell is seen to be generally not feasible. Only for the lower shell delivery velocities, represented by the 500-feet-per-second condition, can the shell be fitted with a rocket motor capable of slowing the shell to a halt above a target over a reasonable short agent discharge path, yet also allow an agent payload to be carried.

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* Integral of rocket velocity.

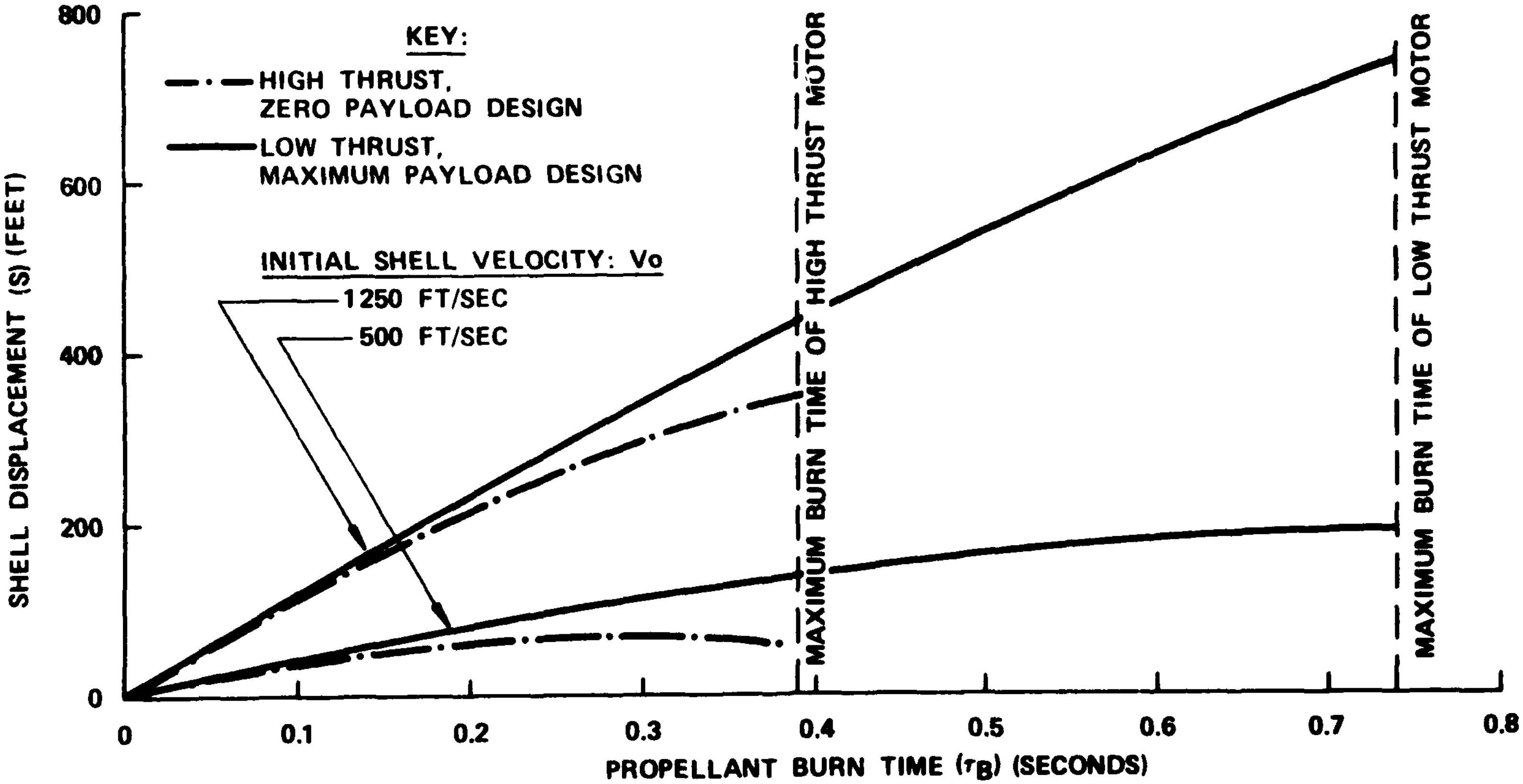

Figure 7. Shell Displacement at End of Propellant Burn

The calculations were based on generally conservative assumptions and it is likely that somewhat more favorable results could be obtained by optimizing individual design parameters. The approach which must be taken is to design the rocket motor for greater thrust to retard the shell more effectively and for less volume to permit greater agent payload. The 4-lb payload available in the low-thrust design of this study is less than one-half the payload carried in the XM687. To meet the desired-performance criteria, a more sophisticated nozzle design is needed which would be shorter in length yet provide adequate exhaust-gas-flow characteristics and chamber pressures. A propellant composition and grain configuration is needed which would provide higher energy density and greater available surface area in a shorter length. The heavy shell casing has the advantage of allowing the use of much higher energy, higher pressure propellants. Refinement of the elementary piston and axial discharge tube design could also provide greater cavity volume for the payload.

In order to minimize shell displacement before impact, short discharge times are required. For this study, times of less than 1 second were considered and it was assumed the system would be able to function in these times. While complete discharge of 3.2 gallons of agent was accomplished in 1.2 seconds from the experimental unit, response of the system at much shorter times would have to be determined. The lower limit of discharge time would be set by the available pressure generated by the propellant and the restriction presented by the discharge tube. A large diameter tube would minimize this restriction, but a small diameter tube would be desirable for maximizing available internal shell volume.

The "retro-rocket" modified artillery shell is a volume-limited design. For the purposes of this study it was assumed that the modified shell weighed the same as the conventional round. However, because of the low cross-sectional densities of the nozzle, propellant, and discharge tube, additional weight would have to be added to the round to permit use of the existing firing tables.

The full success of this munition application is basically limited by two factors. One is the shell's high inert weight per unit volume which requires the use of a high-thrust rocket motor to decelerate the shell effectively. As was shown, the fixed diameter and length of the XM687 casing prohibits the design of the high-thrust rocket motor needed for this application. The second factor is the wide range in shell velocities which must be accomodated. The velocity range of 500-1,250 feet per second results in a range in shell displacement of several hundred feet for a given propellant burn time. As a result, neither a common fuze setting nor rocket motor design can be used for all firing conditions and provide effective delivery of agent to the target. For a motor having a given propellant burn time, variable fuzing must be used which can be set to function at specific altitudes which vary directly with each shell delivery velocity as dictated by the firing zone and elevation used. Otherwise agent discharge would be completed far above the target under lower velocity conditions or the shell would impact before discharge was completed for higher velocity conditions. Such compensation, however, would still result in agent being discharged over unacceptable long flight paths for shell velocities above 500 feet per second so that little agent would reach the target. To insure maximum discharge close to the target for these higher shell velocities, a choice of shells having rocket motors of proportionally greater thrust and/or shorter burn times would have to be available at the firing site: an undesirable logistic requirement.

Use of the propellant as a source of hot, high-pressure, and high-velocity gases to discharge and transport the agent, rather than as primarily a source of thrust for retarding the shell, is an alternate application of this dissemination concept. A rocket motor used only for the purpose of agent discharge would be designed to minimize nozzle and propellant length, to maximize available payload volume, and minimize burn time for rapid discharge.

Two additional phases of the "retro-rocket" dissemination process require study to evaluate more fully the potential of this concept for agent dissemination. The first is the characterization of the agent plume produced by injection of the agent into the rocket exhaust stream. The effects of discharge orifice size, design and location, exhaust temperature and velocity, and munition velocity on plume behavior must be determined. Secondly, plume-ground interactions must be evaluated to determine the extent of cloud spread, turbulence, and the dissemination efficiency of the system.

While this feasibility study indicates the "retro-rocket" concept may have limited adaptability to an artillery shell system, other delivery systems should offer greater potential. An aerial bomb might be a reasonable candidate. It can be constructed of lightweight materials to reduce its inert weight since it is not subjected to the setback forces of an artillery shell, and, as a bomb is not volume-limited, its payload is not restricted. Equipped with drag fins, the approach velocity of a bomb could be reduced to a suitable low and uniform value which would permit use of both a single fuze delay for retrofire and a single rocket motor design. A chemical rocket is also a potential delivery system due to its inherently favorable design and the possibility of using the same rocket motor for both the initial firing of the round and for retrofiring and agent discharge at the target. Applications in which the propellant is used only to project agent also should be considered, such as chemical mines, man- or tank-carried weapons, and for the nonhazardous dissemination of nontoxic agents.

IV. CONCLUSIONS

It was found that:

1. Modification of an artillery shell to function as a "retro-rocket" disseminator is not feasible.

2. The limited volume and high weight of an artillery shell does not allow the use of rocket motors which are sufficiently powerful to meet all operating conditions.

3. As compared to a conventional artillery shell, agent payload is reduced because of the significant internal volume required by the rocket motor.

4. Compensation for the wide range in velocities characteristic of artillery shells, by adjustment of fuze settings and use of alternate rocket motors, would be necessary to provide uniform agent discharge at the target.

5. The feasibility of the "retro-rocket" dissemination concept should be evaluated for other munition applications which do not present the uniquely severe design restrictions of an artillery shell.

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